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The Impact of the 2011 Off the Pacific Coast of Tohoku Earthquake on the Tsukuba 32-m VLBI Station

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Abstract

A 9.0-magnitude earthquake named “the 2011 off the Pacific coast of Tohoku Earthquake” hit eastern areas of Japan on March 11. The gear wheel for the elevation drive of the Tsukuba 32-m VLBI antenna swayed due to the earthquake, but there was no critical damage to the antenna or other equipment. Many aftershocks followed in the few weeks afterwards. Tsukuba 32-m returned to IVS VLBI observing on April 4. The observed VLBI sessions produced VLBI positions for Tsukuba, and co-seismic and post-seismic displacements were detected by VLBI. By the way, GSI has installed and maintains over 1,200 GNSS-based control stations, a large number of triangulation points, and benchmarks throughout Japan. Since the crustal displacement was widespread and its magnitude was very large, we needed to revise the coordinates of many control points. This revision covered the eastern half of Honshu Island with 438 GNSS-based control stations, approximately 43,000 triangulation points, and approximately 1,400 benchmarks. New coordinates, except for these benchmarks, were calculated based on the amount of displacement detected by VLBI on May 10.

1. Japan Having a Lot of Earthquakes

Since the year 1900, a lot of massive earthquakes have occurred in the world. It is said that the largest earthquake in recorded history is the Valdivia Earthquake (Chile) in 1960 with a magnitude of 9.5. The 1964 Alaska Earthquake is the next largest. In recent years, an Mw 9.1 earthquake occurred near Sumatra Island, Indonesia in 2004, and a major earthquake struck Chile again in 2010. The megaquake that hit Eastern Japan in 2011 needs also to be ranked as one of the biggest earthquakes, comparable to the previously mentioned quakes.

The Japanese archipelago is located on the boundaries of four tectonic plates: the Eurasian Plate, the North American Plate, the Pacific Plate, and the Philippine Sea Plate. Many earthquakes around Japan have occurred along the subduction zones of the Pacific Plate and the Philippine Sea Plate. The Tohoku Earthquake of 2011 was also a typical plate-boundary-type earthquake that occurred where the Pacific Plate subducts under the North American Plate. The Geospatial Information Authority of Japan (GSI) installed four VLBI stations: Tsukuba and Shintotsukawa on the North American Plate, Aira on the Eurasian Plate, and Chichijima on the Philippine Sea Plate; and GSI has been conducting VLBI observing sessions. The velocities of these plates are detected by the global analysis of VLBI data. According to the VLBI analysis, the Philippine Sea Plate and the Pacific Plate have large velocities toward the Northwest. The Eurasian Plate, on which Aira and Shanghai are located, moves with a velocity of 3 cm/year toward the Southeast (Figure 1).

In Japan, there have been several major earthquakes since early times. One of the most famous earthquakes is the Great Kanto Earthquake of 1923. This earthquake hit the capital of Tokyo directly and caused quite a lot of harm to a lot of people. Recently, the Mw 6.9 earthquake (the Hanshin-Awaji Earthquake) hit Kobe, one of the largest cities in Western Japan. As this earthquake occurred in the early morning, a lot of fires broke out in the central area of Kobe. Because the hypocenter was near the urban area, many buildings and constructions collapsed. The collapse of the Hanshin Expressway made headlines throughout the world as a symbol of destruction caused by the earthquake.

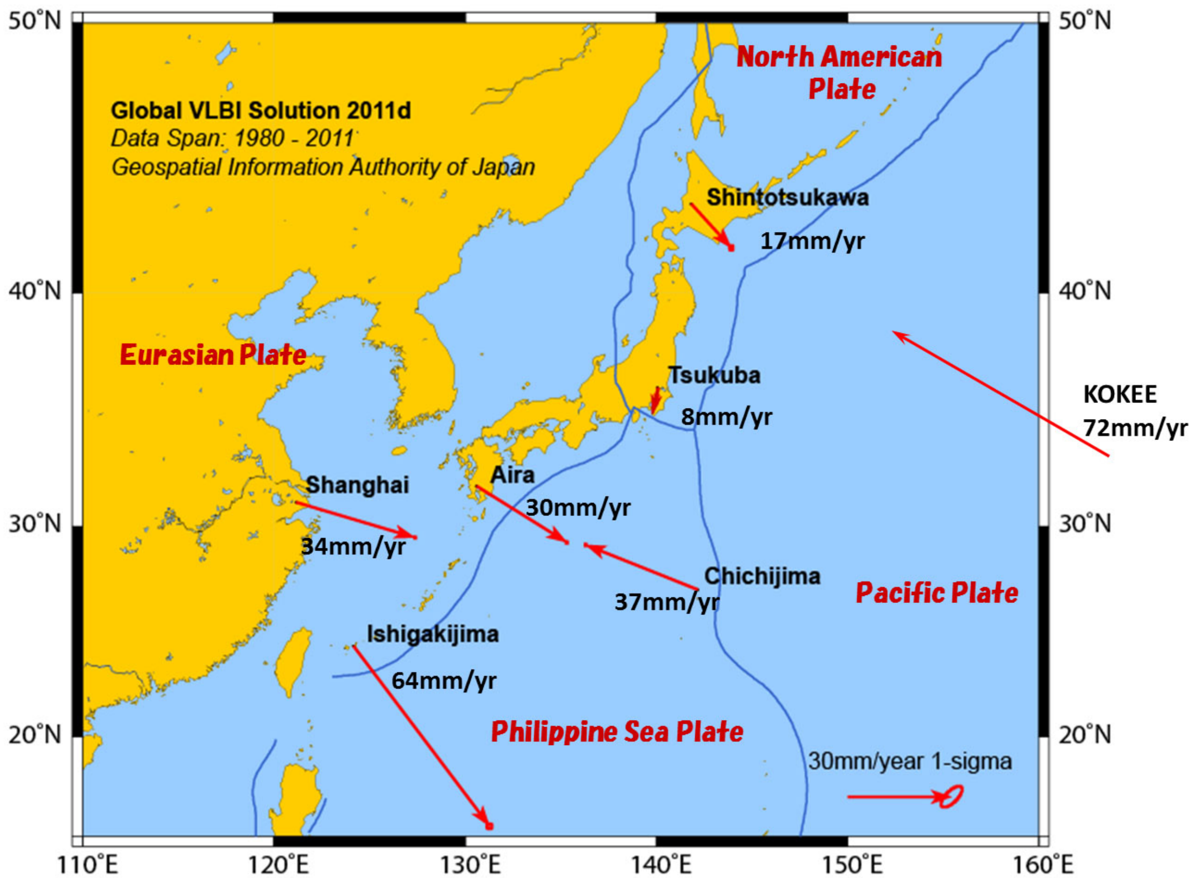

Figure 1. Plate velocities around Japan.

2. 2011 Off the Pacific Coast of Tohoku Earthquake

The earthquake occurred at 2:46 p.m. JST on 11 March 2011. Its official name by the Japan Meteorological Agency (JMA) is "the 2011 off the Pacific coast of Tohoku Earthquake". The epicenter was reported to be at 38°6′12″ North latitude, 142°51′36″ East longitude, 24 km deep, 130 km off the East coast of the Oshika Peninsula. The JMA initially reported the earthquake as a magnitude 7.9 on the JMA magnitude scale (Mj), and quickly revised it up to 8.4 , then to 8.8, and then finally to Mw 9.0 on March 13. Following the main shock, a 7.6 aftershock happened off the coast of Ibaraki at 3:15 p.m., two other massive aftershocks of Mj>7.0 followed within less than an hour after the main event. In the one-year period up to 26 April 2012, some 669 aftershocks of Mj>5.0 were registered; 102 of these were larger than Mj 6.0 and six exceeded Mj

7.0. The earthquake triggered powerful tsunami waves. The JMA tide gauge station at Soma in the Fukushima Prefecture observed a 9.3-meter-high tsunami wave. The tsunami rose to over 40 m at Miyako City in the Iwate Prefecture. Tsunami waves arrived as far away as the West coasts of the United States and Chile. More information is shown in Table 1.

Table 1. Earthquake Summary.

Date	11 March 2011
Time	14:46 JST (05:46 UTC)
Epicenter	130 km ESE off Oshika Peninsula Latitude: 38°6′12″ N Longitude: 142°51′36″ E
Depth	24 km
Magnitude	Mw 9.0
Tsunami	9.3 m or higher at Soma (Fukushima Pref.)
Largest aftershock	Magnitude 7.6 at 11 March 2011 15:15 JST (06:15 UTC)
Casualties	15,858 deaths, 6,077 injured, 3,057 people missing
Damage	Fully-destroyed buildings: 129,527, Partially-destroyed buildings: 256,877

3. Damage in Tsukuba and Kashima

Tsukuba City, where GSI is located, is about 300 km southwest of the epicenter. The main shock caused a blackout for two days and an interruption in the water supply for three days. Roof tiles of many residential buildings came down; boundary fences and walls collapsed. Meanwhile, in Kashima, where the National Institute of Information and Communications Technology (NICT) is located, the damage was much worse: tsunami waves swamped the area and railway tracks near NICT were twisted (Figure 2). The buildings at NICT and the 34-m VLBI antenna were also damaged.

The gear wheel for the elevation drive of the Tsukuba 32-m VLBI antenna swayed because of the earthquake and some of the computers in the Correlator room fell down and broke. However, most of the equipment of the Tsukuba VLBI Station and Correlator survived with only minor damage. Since we were concerned about aftershocks, we suspended VLBI operations for a while.

4. Crustal Displacement Observed by GEONET

The GNSS Earth Observation Network System (GEONET), which is established and maintained by GSI and consists of 1,240 points of GNSS-based control stations, observed the largest displacement that it had seen in its almost 20-year lifetime. At the GNSS station “Oshika” in the Miyagi Prefecture close to the epicenter, displacements of 5.3 m in the horizontal and -1.2 m in the vertical were registered (Figure 3). These values comprise the co-seismic displacements of the

Figure 2. Twisted railway tracks near Kashima (Photo by T. Kondo).

main shock and several aftershocks plus the post-seismic movement in the first five hours after the megaquake. Most parts of Eastern Japan moved to the Southeast or East and subsided by the co-seismic displacement. As of 31 October 2011, 0.79 m of post-seismic movement was detected at the GNSS station “Yamada” in the Iwate Prefecture [1].

5. Restarting VLBI Operations and the Results

VLBI operations at Tsukuba started again on 4 April 2011 with session R1477, 24 days after the earthquake. The seismic displacement (co-seismic plus post-seismic) detected by this session was (E,N,U) = (65.1, 1.9, -6.7) (cm) (Figure 4). The additional post-seismic movement detected by VLBI over the 315 days since this session was (17.0, -4.5, 1.3) (cm).

Tsukuba 32-m is one end of the baseline of the UT1 Intensive session series Int2. The position variation at Tsukuba 32-m due to the co-seismic displacement and a long-running post-seismic motion have an influence on the estimation of UT1-UTC. We applied the correction provided by NASA/GSFC to the post-earthquake position of Tsukuba 32-m in the operational analysis of the UT1 Intensive sessions. The estimated value of UT1-UTC is consistent with the weekday Intensives (Int1) on the Kokee-Wettzell baseline.

6. Revision of Survey Results of Control Points

GSI has installed and maintained not only GNSS-based control stations but also a large number of triangulation points and benchmarks throughout Japan for the purpose of infrastructure for administration of the country. They have published survey results of them (coordinates of control points) which are used for the public surveys conducted by local governments. According to the Survey Act, Article 31, in the case where the position is changed, for instance, by an earthquake, GSI shall revise the coordinates of the control points.

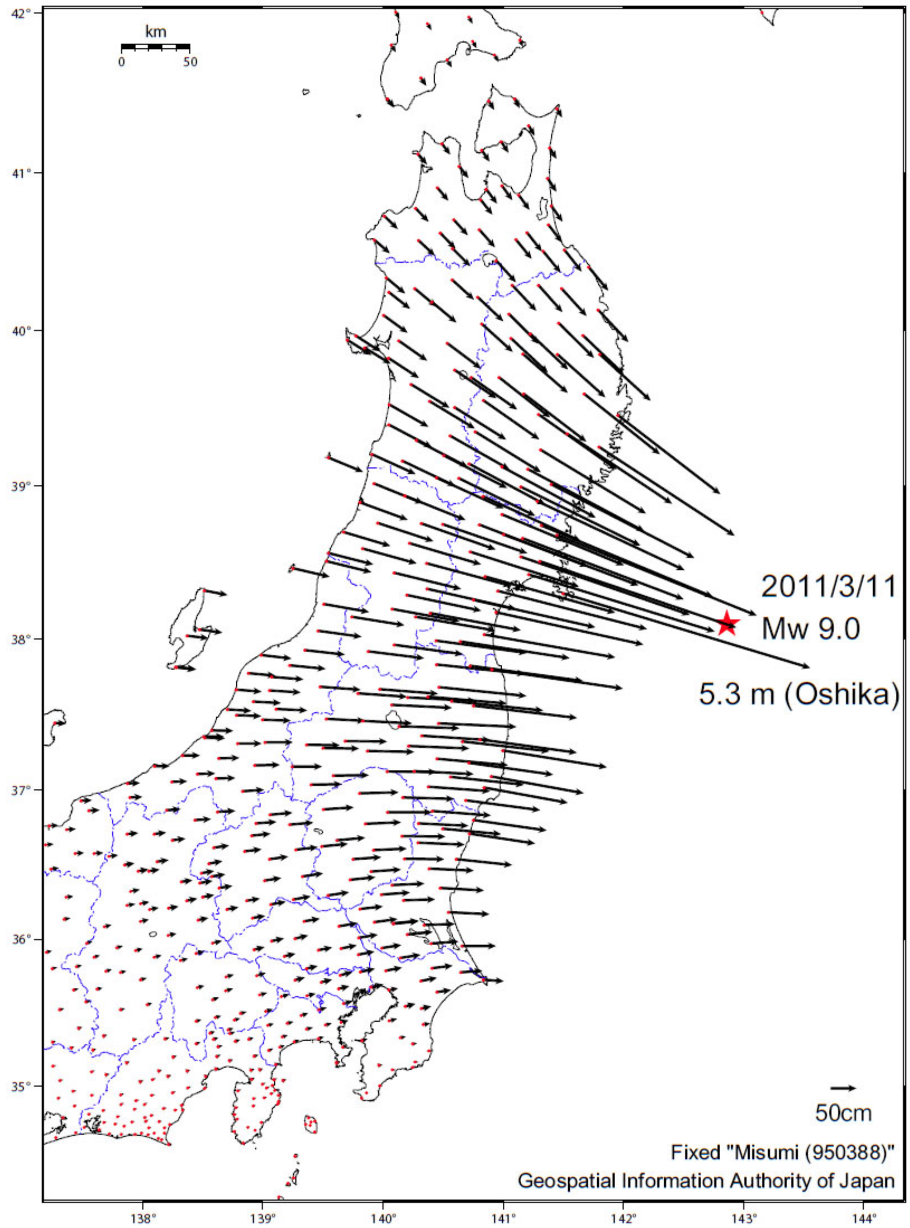

Figure 3. Crustal displacement detected by GEONET.

After the March 11 earthquake, GSI determined that the revision area was where the maximum shear distortion exceeded 2 ppm and interrupted to publish the survey results in this area on 14 March 2011. In case of a narrower revision area, the coordinates of the revised control points were calculated by using coordinates of some GNSS-based control stations outside of the revision area as given coordinates. However, since the crustal displacement was widespread and its magnitude was very large, we decided to use the estimated VLBI position of the Tsukuba 32-m antenna as a practical origin coordinate of revising the control points. The VLBI position in the ITRF2008 frame was determined by an international VLBI session (R1482) on 9–10 May, giving a strong constraint

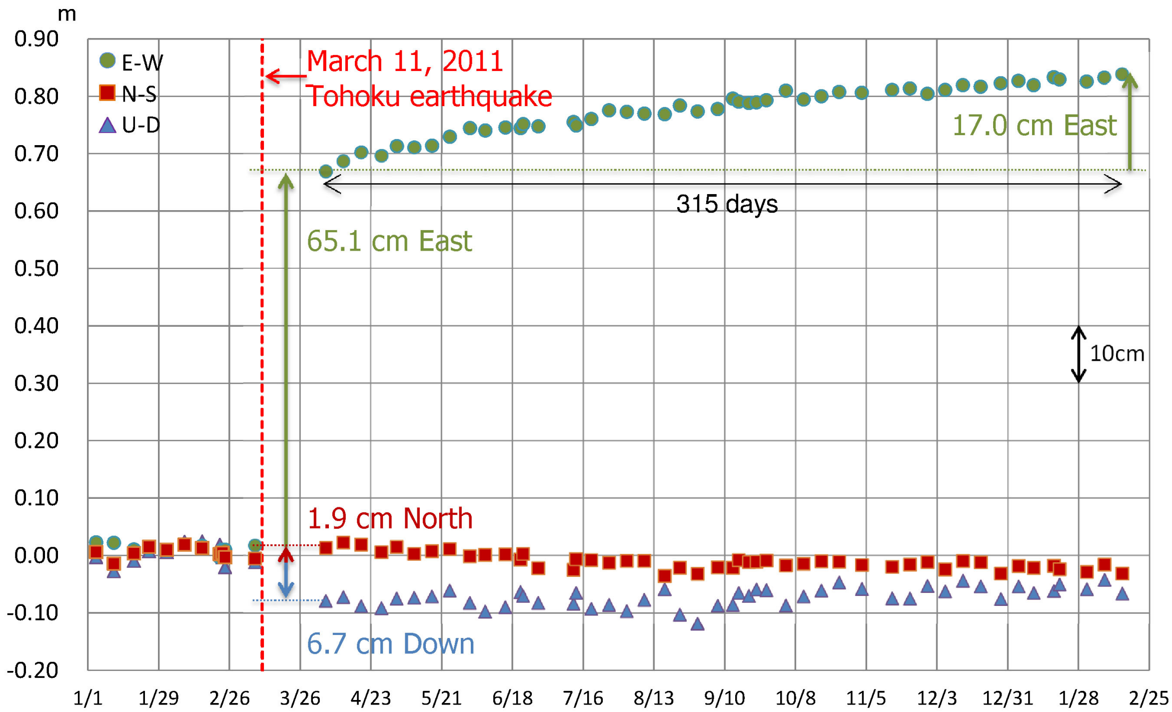

Figure 4. Tsukuba 32-m position variation by VLBI observations.

to the five stations that participated in this session beside Tsukuba. Then the position of the IGS station TSKB was calculated by adding the co-location vector from VLBI to TSKB. Furthermore 438 of the GNSS-based control station coordinates in the revision area were calculated. These coordinates were published on 31 May 2011, two-and-a-half months after the March 11 earthquake [2]. The coordinates of the other control points were calculated by resurveying or applying the adjustment parameter, and published on 31 October 2011. As a result, out of 45,674 control points, 35.3% in Japan were revised (Table 2).

Table 2. Number of revised control points.

Type of control point	**Number of points (revised/total)**
GNSS-based control stations	438/1,240
Triangulation points	43,857/109,074
1st-order	353/975
2nd-order	2,140/5,060
3rd-order	15,170/32,326
4th-order	26,194/70,713
Benchmarks	1,379/18,239
Total:	45,674/128,553 (35.3%)

7. Summary

The Tohoku Earthquake and great tsunami inflicted enormous damage on Japan. Even in the Ibaraki Prefecture, where GSI and NICT are located, many roads and buildings were damaged. GSI observed larger displacements than ever before by using space geodetic techniques (GPS and VLBI), the results of which became well-known throughout the world. The post-earthquake position of the Tsukuba VLBI station became the practical origin of the revised control points which is 35% of total control points in Japan.

The government of Japan spent a huge additional budget for rehabilitation and reconstruction. In this budget, we submitted the proposal for constructing a new VLBI2010 antenna and it was approved. In view of major earthquakes anticipated in the near future, GSI will complete the new VLBI2010 station and continue the international VLBI observation.

References

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[2] Hiyama, Y., et.al., Revision of Survey Results of Control Points after the 2011 off the Pacific Coast of Tohoku Earthquake, In: Bulletin of the Geospatial Information Authority of Japan, Vol. 59 December, 31–42, 2011.